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Published in:
Astronomy and astrophysics

DOI:
10.1051/0004-6361:20030701

[letterpaper]aa520 natbib,amssymb,graphicx ();a,

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Mass loss and rotational CO emission from Asymptotic Giant Branch stars

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Received / Accepted

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We present submillimeter observations of rotational transitions of carbon monoxide from $J = 2 \rightarrow 1$ up to $7 \rightarrow 6$ for a sample of Asymptotic Giant Branch stars and red supergiants. It is the first time that the high transitions $J = 6 \rightarrow 5$ and $7 \rightarrow 6$ are included in such a study. With line radiative transfer calculations, we aim to determine the mass-loss history of these stars by fitting the CO line intensities. We find that the observed line intensities of the high transitions, including the $J = 4 \rightarrow 3$ transition, are significantly lower than the predicted values. We conclude that the physical structure of the outflow of Asymptotic Giant Branch stars is more complex than previously thought. In order to understand the observed line intensities and profiles, a physical structure with a variable mass-loss rate and/or a gradient in stochastic gas velocity is required. A case study of the AGB star WX Psc is performed. We find that the CO line strengths may be explained by variations in mass-loss on time scales similar to those observed in the separated arc-like structures observed around post-AGB stars. In addition, a gradient in the stochastic velocity may play a role. Until this has been sorted out fully, any mass loss determinations based upon single CO lines will remain suspect.

Introduction sec:intro$_co$

Low and intermediate mass stars ($1 < M < 8\,M_\odot$) end their life on the red giant branch and asymptotic giant branch [AGB; see][and references herein]H$_9$6$_r$$eview.DuringtheAGBphase,thestarshaveveryextendedtenuousatmosphe$ $richenvelopethroughadenseanddustystellarwind.IncaseofOH/IRstars,mass-lossratescanbesohighthatthedustshellcomp$ K, dust formation occurs, and a dust driven wind will develop. The mass-loss rates increase from $\dot{M} \approx 10^{-7}$ to a few times 10^{-5} $M_\odot$ yr^{-1}, while the AGB star evolves from the Mira phase to an OH/IR star VH$_8$8$_I$$RAScolors.Recently,ithasbeensuggestedthathighermass-lossratescanbeachievedforoxygen-$ $richAGBstars.JST_96_OH26findthatOH26.5{+}0.6hasundergonearecentincreaseinmassloss,leadingtoacurrentrateof5.5$ $\cdot 10^{-4}\,M_\odot$ yr^{-1}, a result recently confirmed by FJM$_0$2$_o$$h26.Evenhighermass{-}lossrateswerefoundforanotheroxygen{-}$ $richAGBstar,IRAS16342\text{-}3814,forwhichthemass{-}lossratemaybeashighas{\sim}10^{-3}\,M_\odot$ yr^{-1} DWK$_0$2$_I$$RAS16342.Asimilarr$ $M_\odot$ yr^{-1} is found for the carbon-rich evolved star AFGL 2688 SMB$_9$7$_E$$gg$.

AGB stars are important contributors of dust to the interstellar medium (ISM); it is estimated that a substantial fraction of the interstellar dust is produced by oxygen-rich AGB stars [e.g.][]G$_8$9$_s$$tardust.Intheoutflowofevolvedstars$ $richchemistrythedustcompositionisdominatedbysilicates,bothamorphousandcrystalline[e.g.][]SKB_99_ohir,MWT_02_xsilI.T$ $infraredspectraofAGBstarsseemstobecorrelatedwithahighopticaldepthintheamorphoussilicateresonanceat9.7\mu$m and hence a high mass-loss rate WMJ$_9$6$_m$$ineralogy,CJJ_98_ohir,SKB_99_ohir.Thiscouldbeinterpretedasevidencethatacertaint$ $lossrates.Therefore,therelationbetweenmass-lossrateandcrystallinityremainsunclearatpresent.$

In order to further study the correlation between the wind density and the dust composition, reliable mass-loss rates should be determined. Mass-loss rates of AGB stars can be obtained from the thermal emission from dust, predominantly coming from the warm inner regions [e.g.][]B$_8$7$_d$$ustshells.Theycanalsobeinferredfromobservat$ $\rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of both O-rich and C-rich AGB stars. (Hereafter we will use for these rotational transitions the notation CO(1$-$0) etc.) The mass-loss rates of a large number of objects from the catalogue are derived. However, the derived mass-loss rates seem to be underestimated for OH/IR stars, compared to the dust mass loss. HFO$_9$0$_d$$eficiencyhavestudiedthecorrelationbetweenIRAScoloursandmass-$

$lossratesderivedfromCO(2\text{-}1)andCO(1\text{-}0)observations. In the case of very massive dust shells, they find that the intensity of the$
$0)transition is too low compared to the CO(2\text{-}1) transition, which they suspect to be due to a mass-loss rate increase over time. This t$
$loss rate with a factor of \sim 100.$

As the inner regions are warmer they are better probed by higher rotational transitions. Thus a sudden density jump should be detectable in the CO lines. Model calculations by $JST_96_OH26 have demonstrated this effect for OH26.$
$3). Unfortunately this transition is not sufficiently high to firmly establish the recent onset of a superwind, as its excitation temp$
$1) transition and the upper limit obtained for the CO(1\text{-}0) transition, assuming a constant mass-loss rate. Similar results are rep$

The work presented here aims to determine the mass-loss history of a number of oxygen-rich AGB stars with an intermediate or high optical depth in the near- and mid-infrared. For the first time, observations of rotational transitions up to CO (7−6) have been obtained (T_{ex} = 155 K) which probe the more recent mass-loss phases. In Sect. sec:obs we describe the observations and data analysis. Sect. sec:conditions describes the model. Our results are discussed in Sect. sec:analysis. Concluding remarks and an outlook to future work is presented in Sect. sec:disc.

Observations and data reduction sec:obs

Instrumental set-up sec:setup

table Technical details of the JCMT heterodyne receivers. The columns list the used receivers, the frequency windows at which they operate, the observable CO rotational transition, the beam efficiency η_{mb} and the half power beam width (HPBW). center tabularl c c c c receiver Frequency CO transition η_{mb} HPBW

Observations of the ^{12}CO(2−1), (3−2), (4−3), (6−5) and (7−6) rotational transitions in the outflow of evolved stars were obtained during several observing periods between April 2000 and September 2002 using the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. For this purpose, all five different heterodyne receivers available at the JCMT were used, including the new MPIfR/SRON E-band receiver which operates in the 790–840 GHz frequency range. A description of this new receiver is given in Sect. sec:E-band. The technical details and beam properties of the JCMT set up with the appropriate heterodyne receivers are summarized in Table tab:efficiencies. Observations with the B3- and W-receivers were performed in double sideband (DSB) and dual polarization mode. The DSB mode was also used for the observations with the MPIfR/SRON E-band receiver. The bandwidth configuration of the receiver, and hence the spectral resolution was determined by the expected line width of the CO lines. We used bandwidths of at least twice the expected line width to have a sufficiently broad region for baseline subtraction. Estimates for the line width – which is determined by the outflow velocity – were based on published values of line widths of the CO(1−0) transition [e.g.][and references herein]LFO_93_CO.

We used the beam-switching technique to eliminate the background. The secondary mirror was chopped in azimuthal direction over an angle of 120″. Over these small angles the noise from the sky is assumed to be constant. In case of extended sources we used a beam-switch of 180″.

The MPIfR/SRON 800 GHz receiver sec:E-band

The observations of the CO(7−6) line were made with the MPIfR/SRON 800 GHz receiver in October 2001. This PI system is in operation at the JCMT Cassegrain focus cabin since spring 2000. The receiver consists of a single-channel fixed-tuned waveguide mixer with a diagonal horn. The mixer consists of a Nb SIS junction with NbTiN and Al wiring layers fabricated at the University of Groningen, The Netherlands. Details on the fabrication of similar devices can be found in $JDL_00_E. Measured receiver temperatures at the cryostat window are T_R$
550 K DSB. The receiver has an intermediate frequency of 2.5 − 4 GHz. System temperatures including atmospheric losses varied between 6000–14000 K (SSB) at the time of the observations. The beam shape and efficiency have been determined through observations of Mars and yield a deconvolved half power beam width (HPBW) of 6″ and a main beam efficiency η_{mb} of 24%.

Observations and data reduction sec:subobs

Our sample of evolved stars is given in Table tab:obslist, which also indicates the distances towards the programme stars. The sample includes AGB stars and red supergiants. In Table tab:obsdetails an overview of the observed transitions is given, including cumulative integration times and the observing date. The data were obtained over a long period from April 2000 until September 2002 in flexible observing mode, and are part of a larger ongoing programme. During the observations, spectra of CO spectral standards used at the JCMT were also obtained. If necessary, a multiplication factor was applied to the observations of our sample stars, to correct for variations in the atmospheric conditions. These factors are listed in Col. 4

of Table tab:obsdetails and are based on measured standard spectra. Reliable standards are only available for the transitions observed with the A3-, B3- and W/C-receivers, for which the flux calibration accuracy is around 10%. For the W/D- and MPIfR/SRON E-band reliable standards for our lines of interest are lacking. Therefore we estimate that the absolute flux calibration in these bands has an accuracy of 30%.

Table tab:efficiencies lists the beam efficiencies η_{mb} for all receivers. The main beam temperatures were calculated according to $T_{mb} = T_A^*/\eta_{mb}$, where T_A^* is the measured antenna temperature. These main beam temperatures can directly be compared to observations from other telescopes.

figure [width=8.5cm]H4224F1.eps

Correction of the profile of the CO(3−2) transition of VX Sgr. The dotted line represents the observation in which the interstellar contribution is clearly visible. Ignoring the interstellar contribution results in the solid line, which is used to obtain the integrated intensity. fig:correct